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Life cycle assessment of decentralized mobile production systems for pelletizing logging residues under Nordic conditions

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ABSTRACT

The development of mobile systems for the decentralized pelletizing of forest-based residual biomass is currently underway. However, there is a lack of knowledge regarding the environmental impacts of such systems that needs to be developed for correct judgements on the most sustainable developing paths. The objective of this study was to quantify and compare the environmental impacts of a decentralized mobile production system for pelletizing logging residues in Northern Sweden operating at either the forest landing or forest terminal from a Life Cycle Assessment (LCA) perspective.

The results showed that the landing- and terminal-based scenarios showed similar environmental profiles. The pelleting, transportation and drying stages of both scenarios were identified as environmental *hotspots*. These production stages accounted for 62%, 14% and 14% of the total greenhouse gas emissions, respectively. Key factors influencing the system were the use of electricity at terminals, the increase in pelletizer capacity, and long transportation distances. The use of a Swedish electricity mix instead of diesel based electricity in the terminal-based scenario reduced all of the environmental impacts by between 68% and 83%, with the exception of fresh water eutrophication potential, which increased by 26%.

In conclusion, our findings indicate that an electrified mobile pellet production system with high operational efficiency and situated at a terminal close to the harvesting sites could, from an LCA point of view, be an interesting option for pelletizing Nordic logging residues, especially in regions with long transportation distances to industry.

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1. Introduction

The transition to a European bioeconomy requires a sustainable, as well as cost- and energy efficient, supply of quality biomaterials for the biorefining industry. The development of cleaner and renewable energy sources are necessary to reduce the environmental pressures and fossil fuel dependency (Uasuf and Becker, 2011). Consistent quality, particle size and moisture content of feedstock are essential factors for biorefinery processes (Kudakasseril Kurian et al., 2013). Nordic countries have access to vast forest-based feedstock resources that could be utilized in a sustainable manner (Routa et al., 2013). For example, residual forest biomass, such as the logging residues (tops and branches) that result from regeneration cuttings in Northern Sweden, show great potential as an input for several biorefining processes (Bergström and Matisons, 2014). However, the bulky and heterogeneous nature of biomass may necessitate densification before transportation over long distances (Bergström et al., 2010; Eranki et al., 2011; Kudakasseril Kurian et al., 2013). Although an increase in biomass transportation to biorefineries is expected in the near future (Kudakasseril Kurian et al., 2013), the high transportation costs of

Acronym list: CCP, climate change potential; CO_2-eq., CO_2-equivalents; FDP, fossil fuel depletion potential; FEP, fresh water eutrophication potential; GHG, greenhouse gas; kg, kilogram; L, landing-based scenario; LCA, life cycle assessment; MEP, marine eutrophication potential; MJ, megajoule; N-eq., nitrogen-equivalents; NMVOC, non-methane volatile organic carbon compound; P-eq., phosphorus-equivalents; ODt, oven dry metric tonne; Oil-eq., oil-equivalents; PM_h, productive machine hours; POFP, photochemical oxidant formation potential; SO_2-eq., sulfur dioxide; t, metric tonne; T, terminal-based scenario; TAP, terrestrial acidification potential.

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logging residues is a barrier to its use compared to other forms of biomass (Mirkouei et al., 2016).

In this sense, during the last decade the global trade of wood pellets has been growing (Mobini et al., 2013). Wood pellets are considered a clean renewable fuel as well as one of the potential substitutes for fossil fuels such as coal and oil for heating and cogeneration (Uasuf and Becker, 2011). Pellets are more suitable for transportation and storage than unprocessed biomass due to low moisture content, high energy density and homogenous shape (Porsö and Hansson, 2014). In 2015, wood pellet consumption in the EU reached 20.3 million tonnes (Aebiom, 2016), and market volumes of pellets are expected to grow by about 25 million tonnes in 2020 (Sikkema et al., 2011).

Pellet production usually occurs at the industry site (centralized production). An alternative to centralized production is to produce pellets close to the raw material source (decentralized production). Eranki et al. (2011) discussed the advantages and challenges of strategically distributed facilities to procure, pre-treat and densify biomass into intermediate products, such as pellets. The densified biomass could be transported economically over longer distances than loose biomass. In addition, small facilities require smaller collection radius for bulky biomass, decreasing transportation cost. This could allow a centralized biorefinery to have a steady supply of uniform biomass from a larger radius, and even allow biorefineries to be located in areas with limited biomass production (Eranki et al., 2011) to increase their production capacity (Kudakasseril Kurian et al., 2013). In addition, according to De Jong et al. (2017) the value of decentralized facilities becomes more relevant when well-sited locations are already taken and the biomass supply becomes more disperse and expensive, which is expected at higher production levels of biorefined products. De Jong et al. (2017) identified two types of decentralized supply chains: linear or hub-and-spoke-type. In the linear type only one pre-treatment plant supplies the upgrading centralized plant, while in the hub-and-spoke-type multiple pre-treatment plants supply the upgrading centralized plant. The authors mentioned that the hub-and-spoke-type faces a loss of economy of scale, and therefore this type of decentralized supply cannot emerge at lower levels of production. De Jong et al. (2017) stated that linear decentralized supply may be preferred over the absence of pre-treatment facilities in cases where there are long distances between the biomass source and end use. However, the decentralized facilities face several challenges to operate successfully, such as possible underusage of equipment, low capacity, high energy and cost requirement of grinding and densification processes, and dry matter losses between harvest and pellet production (Eranki et al., 2011) which was identified by Kudakasseril Kurian et al. (2013) as the primary parameters to characterize the efficacy of a pretreatment process. Thek and Obernberger (2004) analyzed the production costs for wood pellets in Austria and Sweden. Their calculations showed that pellet production is possible in small- and large-scale plants. However, the authors pointed out that the risk of a non-economic pellet production is higher for small-scale systems. According to Mangoyana and Smith (2011), economic factors are more important in driving the development of small-scale decentralized bioenergy systems than environmental factors. In this way, production efficiency is essential to ensure overall sustainability of such systems, and efficiency improvements could be made by: 1) implementing closed loop models in which waste materials from one process are used in the production of other products for localized use and 2) identifying opportunities for small-scale producers to participate in the biofuel production chain, for example, raw material procurement, refining, distribution and marketing. Furthermore, small-scale decentralized bioenergy systems could provide energy independency, economic development opportunities in rural and/or marginalized areas as well as a way to mitigate climate change (Mangoyana and Smith, 2011).

One advantage of the decentralized facilities is that they can be mobile instead of fixed. Mirkouei et al. (2016) examined the use of mobile refineries in combination with large-scale non-mobile refineries. Their results indicated that the use of mobile along with fixed refineries was a better option when transportation costs and distances increased. The development of mobile systems for the decentralized pelletizing of forest-based residual biomass is currently underway (Mobile Flip, 2017). However, the successful development of such production systems requires an adequate investigation of how they should be designed and managed for high energy efficiency as well as low environmental impacts and cost. Thus, decentralized production systems need to be developed to: 1) enhance value by pre-processing biomaterials closer to the raw material source before transportation to industry and/or 2) produce the final product at, or close to, the raw material source.

Life Cycle Assessment (LCA) is a tool for systems analysis that compiles and evaluates resource consumption and waste generation in order to estimate the potential environmental impacts arising from a production system throughout its life cycle (ISO 14040, 2006). LCA has been extensively used to analyze the environmental profiles of bioenergy systems, wood supply chains and woody products (De La Fuente et al., 2017; González-García et al., 2014b; Lindholm et al., 2011; Murphy et al., 2014; Thakur et al., 2014).

There are many recent environmental studies that have employed LCA to evaluate conventional pellet production systems (Adams et al., 2015; Fantozzi and Buratti, 2010; Hagber et al., 2009; Katers et al., 2012; Laschi et al., 2016; Pa et al., 2011; Porsö and Hansson, 2014; Sikkema et al., 2010; Wang et al., 2017). Laschi et al. (2016) evaluated the environmental impacts of industrial pellet production in Italy. The authors reported that the production of 1 metric tonne (t) of packed pellets results in 400 kg CO_2-eq. when the process is considered from a cradle-to-gate perspective. The production of pellets (i.e. the processes of grinding, drying, pelletizing and packaging) contributed to 95% of the total greenhouse gas (GHG) emissions arising from the pelletizing system. Hagber et al. (2009) estimated default values for conventional production chains in Swedish stand-alone plants that comprised raw material procurement to final pellet use. Their analysis showed that the typical emissions under Swedish conditions were 3–4 g-CO_2 eq. per MJ pellets, which is equivalent to 56–74 kg CO_2-eq. per oven dry tonne (ODt) of pellets when considering an energy content of 18.5 MJ per ODkg pellets (Francescato et al., 2008).

Sikkema et al. (2010) compared conventional wood pellet chains in three European countries from the procurement of feedstock from sawmills to its conversion into heat or electricity. The amount of GHG emissions per t of pellets varied from 50 kg CO_2-eq. to 330 kg CO_2-eq. Pa et al. (2011) calculated the GHG emissions derived from wood pellet production in Canada, including not only their production, but also transportation activities to two different ports. Their calculations yielded GHG emissions of 140 kg CO_2-eq. per t of pellets when the pellets were transported locally (North Vancouver port), and 295 kg CO_2-eq. if marine transportation to Europe was considered (Rotterdam port). In terms of the ratio between the energy spent to produce pellets and their energy content, Laschi et al. (2016) reported an energy ratio of 0.15. However, this ratio, as well as the GHG emissions, can vary depending on industrial scale, machinery efficiency, feedstock used and the considered system boundaries (Laschi et al., 2016). The electricity mix used in production can also greatly influence the results (Hagber et al., 2009). However, all of the mentioned studies are based on stationary industrial plants (centralized production systems). There is currently a lack of knowledge regarding the

environmental impacts of mobile decentralized pellet production systems. Therefore, more information is needed to identify the development path that will lead to the most sustainable solutions. Should the mobile pellet plant work directly at the harvesting site or at a forest terminal? What would be the environmental impacts differences? Which are the environmental *hotspots* in the production systems? Which factors are most influential on the system environmental performance? The objective of this study was to answer those questions by evaluating the environmental profile of small-scale decentralized mobile production systems for pelletizing logging residues in Northern Sweden under two operating scenarios, landing-based and terminal-based. In both scenarios, the feedstocks used were logging residues from forests managed to produce sawlogs and pulpwood as main products. The small-scale pellet production system could contribute to improving the transportation efficiency of biomass, reducing biomass degradability, and producing a high value, homogeneous product. This study provides new knowledge about mobile pellet plants using logging residues as feedstock. This information could be useful for the simulation and design of more efficient supply systems, production management as well as the development of business models.

2. Materials & methods

This study followed the guidelines established by ISO 14040 (2006), which describe the principles and framework for LCA.

2.1. Goal and scope definition

The environmental profiles of woody pellets production from logging residues in North Sweden was assessed considering a gate-to-gate LCA perspective. Two different scenarios were analyzed: a landing-based and a terminal-based scenarios (Fig. 1). The landing-based scenario operates directly at the forest landing site (i.e. a cleared area where wood is collected during extraction in preparation for transportation to the processing facility or final destination), and the terminal-based scenario operates at the forest terminal (i.e. an intermediate site between the forest and the industry where different forest assortments are temporally stored and potentially pre-processed). The environmental impacts of these two scenarios were compared in detail to identify production differences and possible areas for improvement. The studied systems produce and deliver pellets from the forest to storage. Therefore, the functional unit chosen as the reference for all inputs and outputs, as well as for the reporting of environmental impacts, was deliver of one ODt of pellet (one metric tonne at 0% moisture content – Oven Dried tonne) from forest to storage. The specific aims of this research study were: i) to provide information on how different processes contributed to total emissions, ii) to identify the environmental key processes within the production system and, iii) to investigate how on-site raw material concentration, transportation distance, pelletizer production capacity, and the use of electricity at the terminal affect the environmental performance of the overall system.

2.2. Description of the system boundaries and scenarios under study

The forest supply area for the case study was situated in the Örnsköldsvik area in Northern Sweden. The analyzed system operated at both the forest landing (landing-based scenario) and terminal (terminal-based scenario). The same raw material (logging residues), technology, and system boundaries were applied to both scenarios (Table 1 and Fig. 2). The pelletizing process starts with a size reduction of the raw material, which, in this study, means the chipping of logging residues. After chipping, the wood chips are screened in order to improve the chip quality by reducing percentage of fine fraction, oversizes and contaminants such as stones. After screening, the wood chips are dried and hammer-milled to further reduce the size of the chips to that required by the pellet mill. Once the wood pellets leave the press they are cooled and sieved before storage or transportation. Therefore, the production system contained the following stages: chipping, fractioning, drying, pelleting and transportation (Fig. 2). The study assumes that there are no differences in the processing-related biomass losses between scenarios. The total input of logging residues needed to produce 1 ODt of pellets in both scenarios is 1.462 ODt due to losses in chipping, fractioning and sieving processes (10%, 20% and 5%, respectively). If there would have been differences in the biomass losses between the scenarios, the initial amount of biomass needed in each scenario to produce the same amount of pellets would have been different, and this should have been taken into account in the model. In both scenarios, the last step of the production system is the storage of pellets at terminal (the same terminal in both scenarios). The next steps (transportation to final users, biomass upgrading or combustion) in the pellet supply chain are identical in both scenarios. Therefore, they were excluded from the system boundaries. The production and maintenance of the machinery used in both scenarios, as well as the production and maintenance of trucks used for transportation of wood chips, pellets, equipment and workers, were included within the system boundaries of each scenario. The production of other system inputs, such as diesel fuel and lubricants, was also included within the system boundaries.

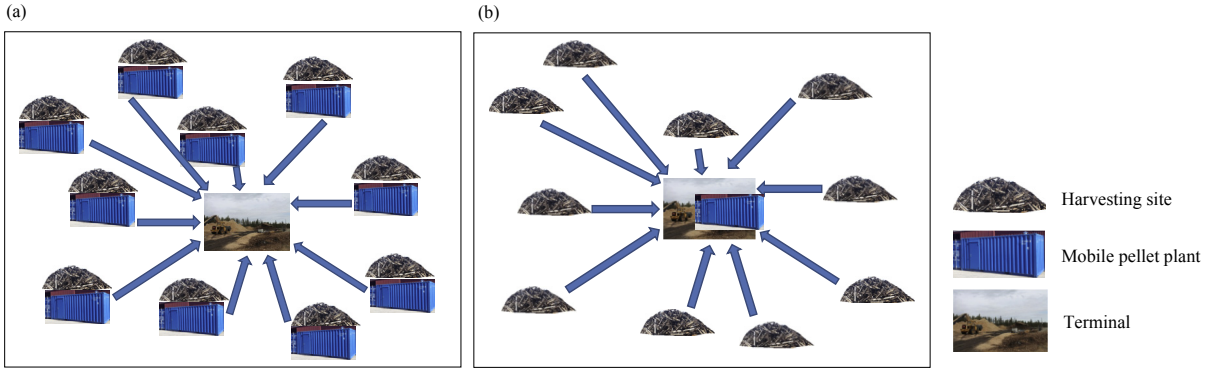

Fig. 1. Scenarios under assessment. a) Landing-based scenario; b) Terminal-based scenario.

Table 1
Processes considered in the analyzed landing- and terminal-based scenarios.

	Process	Terminal- based scenario	Landing-based scenario
1	Chipping at landing	X	X
2	Piling wood chips	X	
3	Loading chips onto fractioning machine	X	
4	Fractioning	X	X
5	Piling sieved wood chips	X	X
6	Piling fines	X	X
7	Loading fines into bio-boiler	X	X
8	Fines combustion	X	X
9	Loading chips into dryer containers	X	X
10	Drying sieved wood chips	X	X
11	Screw conveying of dry chips to hammer mill	X	X
12	Hammer-milling	X	X
13	Water addition (conditioning)	X	X
14	Screw conveying of sawdust to pelletizer	X	X
15	Pelletizing	X	X
16	Screw conveying of pellets to wood pellet cooler with vibration sieve	X	X
17	Cooling and sieving	X	X
18	Screw conveying of fine fractions to pelletizer	X	X
19	Screw conveying of pellets to the storage containers	X	X
20	Transportation of water from industry to landing/terminal	X	X
21	Transportation of workers from accommodation to landing/terminal (once/every 8 h)	X	X
22	Chipper and chipper worker relocation	X	X
23	Landing worker relocation		X
24	Fractioning equipment relocation		X
25	Drying equipment relocation		X
26	Pelletizing equipment relocation		X
27	Loader relocation		X
28	Transportation of wood chips from landing to terminal	X	
29	Transportation of pellets from landing to terminal		X

2.2.1. Raw material specification

Pellets were produced from logging residues (tops and branches) from final fellings. The species composition, according to the National Forest Inventory for the supply area (Swedish Forest Agency, 2017), was 53% Norway spruce *(Picea abies)*, 37% Scots pine *(Pinus sylvestris)* and 10% birch *(Betula* sp.*)*. The average size of a harvesting site and the annual production of logging residues from final felling in the supply area was 7.5 ha and 34 ODt per ha, respectively. It was assumed that logging residues are extracted fresh (within a few days from being cut), stored in piles at landing, and then covered with sheets at the landing for at least two months, during the period April–September, to reduce moisture content to 35% (wet basis).

2.2.2. Pellet quality and quantities

Pellet production of 93 ODt per month was considered in both scenarios and the quality of pellets met the class A2 standards for wood fuel pellets from forest residues, defined in EN 14961-2:2011 as pellet durability $\geq$97.5%, bulk density $\geq$600 kg/m^3, ash content $\leq$1.5%, moisture content $\leq$10%, and a net calorific value of $16.3 < Q < 19.0$ MJ/kg.

2.2.3. Landing-based scenario

A production line was set up at the landing with room for the storage of loose logging residues, the storage of chips and fines, a chipper, a fractioning unit, two drying containers, a hot air generator, a pelletizing unit, and two storage containers. The landings were operational all year around, except for April when forest roads are not accessible due to frost break-off. Ten relocations of equipment were assumed to occur over a time period of twenty months (two months are needed for the processing of logging residues at a harvesting site). Therefore, ten landing areas with the same characteristics were included in the study (Fig. 1).

The pellet production system was divided into five stages: chipping, fractioning, drying, pelleting, and transportation. Logging residues were already at landing; therefore, no extraction of logging residues was included within the system boundaries. Chipping of logging residues was carried out using a truck-mounted drum chipper, which comprises a truck that transports the chipping unit and feeds raw material to the chipper. Chipping losses were assumed to be 10% of oven dry mass (Joelsson et al., 2016). Wood chips were directly loaded from the chipper to the fractioning machine. The fractioning process separated fines from wood chips. Separation of contaminants, such as stones and gravel, was performed with a wind-sifter. The chipper, fractioning machine, and wind-sifter worked as one unit. After fractioning, a front wheeled loader piled the fines and sieved wood chips into different piles. Two dryer containers (30 m^3 capacity per container) with a hot air generator working 24 h per day were used to dry the chip fraction prior to pelletizing. The front wheeled loader was used to load the drying containers and the bio-boiler. Fine fractions obtained after fractioning were used as fuel for the bio-boiler. Dry chips were then screw-conveyed to the hammer mill. The pelleting stage started with hammer-milling of the dry chips. The produced wood powder was then screw-conveyed to the pelletizer. The moisture content of the wood powder was adjusted to 10% by the addition of water (conditioning) before pelletizing. The produced pellets were belt-conveyed to the wood pellet cooler with a vibration sieve and then loaded into truck containers. Sieved off fines were returned to the conditioning point. The pelletizer unit worked 24 h per day.

The transportation of pellets from landing to terminal was carried out by a container truck and trailers. The capacity per container was 35 m^3, and the maximum truck payload was 36 t. The truck delivered two empty containers when arriving for reloading. The relocation of machinery from one landing to the next was carried out by trucks, with the exception of the front wheeled loader that relocated itself (assuming an average speed of 30 km/h). A passenger car was used for the relocation of workers.

The electricity needed for the wind-sifter, hot air generation fan, hammer mill, pelletizer, wood pellet cooler with vibration sieve,

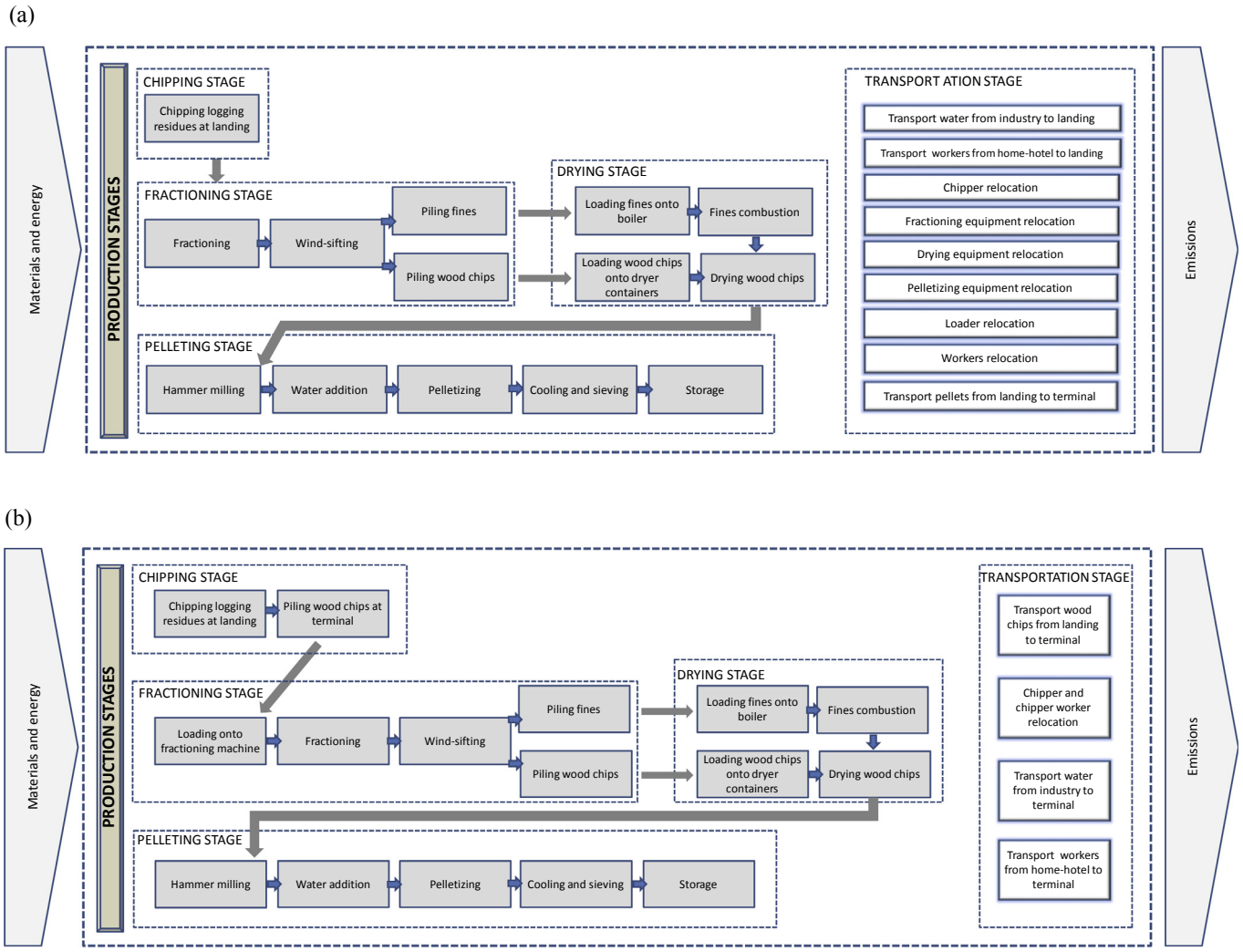

Fig. 2. System boundaries of the two evaluated scenarios. a) Landing-based scenario; b) Terminal-based scenario. The arrows indicate the order in which the processes take place.

and conveyors was produced by a diesel-powered generator. The rest of the equipment considered in the study ran on diesel fuel, except for the bio-boiler, which used fine fractions.

2.2.4. Terminal-based scenario

A 0.5 ha terminal with a production capacity equal to that at the landing, and a chipped logging residue storage capacity of 1400 ODt/year was considered. The terminal had no access to electricity or water and was operational all-year-around.

The terminal-based scenario had the same production line as the previous scenario, with the following exceptions: wood chips were directly loaded into truck containers and transported by container trucks and trailers to the terminal, where they were unloaded and then piled by a front wheeled loader; trucks delivered three empty containers when arriving for reloading; the fractioning machine worked independently of the chipper; a front wheeled loader loaded the chips onto the fractioning machine; only chipper and chipper worker relocations were needed.

2.3. Allocation

The energy and resource requirements of processes that yield two or more products must be appropriately divided between the products. The ISO guideline (ISO 14044, 2006) recommends avoiding allocation whenever possible.

In this study, only woody pellets were considered as product. Therefore, no allocation was performed and all the loads were applied to the pellets.

2.4. Data inventory and input parameters

Data specifically related to pellet production processes (Table 2) were collected from the following sources: time and fuel consumption of the loader, chipper and trucks were taken from Joelsson et al. (2016) and Lindholm et al. (2010); fractioning machine and wind-sifter data were provided by Norditek AB (personal communication with Eric Johansson, Norditek, Sävar, Sweden); data for dryer and pelletizer units, as well as generators, were taken from the web pages of the respective machinery manufacturers (drying system: Tecnofarm (2017) and HB Group (2017); biomass hot air generator: Suntec Energy Systems (2017); pelletizer: SPC Sweden Power Chippers AB (2017); diesel generator: Yancheng Best Engine Manufacturing Co. (2017)); data concerning the amount of available biomass per harvesting site in the study area were taken from Joelsson et al. (2016), which had utilized data from the Swedish National Forest Inventory. Appropriate distances for the relocation of machinery and workers were provided by Norra Skogsägarna (personal communication with Håkan Lagesson, Norra

Table 2
Time consumption, fossil fuel, lubricant oil and electricity consumption, weight and power of machinery used in landing- (L) and terminal-based (T) scenarios. Acronyms: PM_h: productive machine hours; ODt – oven dry metric tonne of biomass produced: wood chips (ODt_c), fines (ODt_f), milled wood chips (ODt_{mc}) or pellet (ODt_p).

Stage	Scenario	Operation	Machinery	Time consumption (PMh/ODt)	Fuel or electricity consumption	Lubricant oil consumption (percentage of fuel used)	Weight (kg) & Power (kW)
Transportation	L, T	Transportation of workers	Passenger car		0.09 l/km	0.2	4077; 180
	L, T	Chipper relocation	Medium truck with crane		0,35 l/km	0.2	13800; 250
	L	Fractioning machine relocation	Truck		0,56 l/km	0.2	19000; 560
	L	Two dryer containers + hot air generator + diesel generator relocation	Container truck		0.56 l/km	0.2	28000; 560
	L	Water tank + hammer mill + pelletizer + wood pellet cooler relocation	Container truck		0.56 l/km	0.2	28000; 560
	L	Two storage pellet containers + conveyor belts	Container truck		0.56 l/km	0.2	28000; 560
	L	Front wheeled loader relocation	Front wheeled loader		2.5 l/km	3	14007; 120
	L	Transportation of pellets from landing to terminal	Container truck		0.56 l/km	0.2	28000; 560
	T	Transportation of wood chips from landing to terminal	Container truck		0.56 l/km	0.2	28000; 560
	T	Transportation of water	Container truck		0.56 l/km	0.2	28000; 560
Chipping	L, T	Chipping logging residues	Truck mounted drum chipper	0.09 PMh/ODt_c	51.1 l/PMh	0.9	22800; 331
	T	Piling wood chips at terminal	Front wheeled loader	0.03 PMh/ODt_c	12.0 l/PMh	3	14007; 120
Fractioning	T	Loading wood chips onto fractioning machine	Front wheeled loader	0.04 PMh/ODt_c	12.0 l/PMh	3	14007; 120
	L, T	Fractioning wood chips	Fractioning machine (starscreen)	0.04 (T) 0.09 (L) PMh/ODt_c	12.0 l/PMh		28000; 130
	L, T	Wind-sifting	Wind-sifter	0.04 (T) 0.09 (L) PMh/ODt_c	20 kW		2500; 20
	L, T	Piling wood chips	Front wheeled loader	0.03 PMh/ODt_c	12.0 l/PMh	3	14007; 120
	L, T	Piling fines	Front wheeled loader	0.03 PMh/ODt_f	12.0 l/PMh	3	14007; 120
Drying	L, T	Loading chips into dryer containers	Front wheeled loader	0.03 PMh/ODt_c	12.0 l/PMh	3	14007; 120
	L, T	Loading fines into bio-boiler	Front wheeled loader	0.03 PMh/ODt_f	12.0 l/PMh	3	14007; 120
	L, T	Drying	Dryer container (30 m^3)		468 kWh/ODt		2500 kg
	L, T	Hot air generation	Biomass hot air generator (120000 kcal/h)	6.7 PMh/ODt_c	5.8 kW		1100; 140
Pelleting	L, T	Loading dry wood chips onto hammer mill	Screw conveyor (6 m)	7.3 PMh/ODt_c (capacity limited by the pelletizer time consumption)	1.5 kW		300 kg
	L, T	Milling wood chips	Hammer mill	7.3 PMh/ODt_c (capacity limited by the pelletizer time consumption)	5.5 kW		250 kg
	L, T	Loading pelletizer, directly from hammer mill	Screw conveyor (2.5 m)	7.3 PMh/ODt_{mc}	1.5 kW		125 kg
	L, T	Water addition	Water tank				2300 kg
	L, T	Pelletizing	Pelletizer	7.3 PMh/ODt_p	15 kW		400 kg
	L, T	Moving pellets from pelletizer to wood pellet cooler	Belt conveyor (2.5 m)	7.3 PMh/ODt_p	1.5 kW		125 kg
	L, T	Cooling and sieving	Wood pellet cooler with vibration sieve	0.4 PMh/ODt_p	1.5 kW		870 kg
	L, T	Returning fine fractions back to pelletizer	Screw conveyor (2.5 m)	3.7 PMh/ODt_f	1.5 kW		125 kg
	L, T	Moving produced pellets to truck containers	Screw conveyor (4 m)	3.7 PMh/ODt_p	1.5 kW		200 kg
	L, T	Pellet storage	Container (35 m^3)				2300 kg
	L, T	Electricity generation	Diesel generator		0.209 kg/kWh		1000 kg

Skogsägarna, Umeå, Sweden). Data from the ecoinvent v3. 2 database® (Wernet et al., 2016) were used for background processes associated with the production of fossil fuels, as well as the production and maintenance of machinery. The ecoinvent processes considered in this study were modified to reflect the specific characteristics of the studied activities (rate of fossil fuel consumption, as well as the weight and lifespan of the machinery used).

The following aspects were also considered:

- Forest inventory data included projections of the available biomass for the next 10 years. The annual potential available biomass was used as basis for calculations.
- 20% of the biomass was separated as fines in the fractioning process.
- 5% of the biomass was recirculated from the pellet vibrating tray to the pelletizing process.
- Wood chips were dried, with moisture content decreasing from 35% to 10% (wet base), and a linear relation between moisture content and drying time was assumed.
- 10 machinery and worker relocations á 30 km (personal communication with Håkan Lageson, Norra Skogsägarna, Umeå, Sweden) were assumed for the landing scenario in order to provide a representative comparison of the two scenarios.
- Machinery production not available in ecoinvent database® (e.g. drying system, wood pellet cooler with vibration sieve, wind-sifter) was compensated as the production of the main materials used in the machinery (e.g. steel).
- The power and weight of the screw conveyors was assumed to be 1.5 kW and 50 kg/m, respectively.
- The lifespan considered for the main pellet production equipment was: 24000 h for the chipper and fractioning machine, 25000 h for the drying system, and 9000 h for the loader and pelletizer.
- Piling and loading fines or wood chips into dryer containers and bio-boiler were assumed to consume the same amount of time.
- The total distance from landing to terminal, and from terminal to accommodation for terminal workers was 37.5 km. This distance corresponds to half way from forest to industry (75 km for final feelings – average distance of the 292 forest inventory plots in the supply area). According to Kons et al. (2014) the average distance from terminal to industry varies from 18 km to 66 km.
- Release of biotic CO_2 from combustion of fines in the bio-boiler were excluded from the calculations since the uptake of CO_2 during forest biomass growth was considered equal to the amount of CO_2 released following the oxidation of forest biomass (Dias and Arroja, 2012; Forsberg, 2000; González-García et al., 2014a; Sultana et al., 2010).

2.5. Life cycle impact assessment

The environmental assessment was conducted according to the characterization factors reported in the ReCiPe (H) midpoint method v.10. (Goedkoop et al., 2009). The potential impacts assessed were climate change potential (CCP) (kg CO_2-eq.), terrestrial acidification potential (TAP) (g SO_2-eq.), marine eutrophication potential (MEP) (g N-eq.), fresh water eutrophication potential (FEP) (g P-eq.), photochemical oxidant formation potential (POFP) (g NMVOC) and fossil fuel depletion potential (FDP) (kg oil-eq.). CCP was chosen because of its relevance in a climate change context. However, processes with positive CCP effects may have negative effects in other impact categories (Klein et al., 2015). Therefore, additional environmental impact categories should be considered in order to provide a comprehensive environmental analysis, and avoid drawing the wrong conclusions. TAP, MEP, FEP, POFP, NMVOC and FDP were chosen because they are common impact categories reported in LCAs of forest systems (Klein et al., 2015; Cherubini and Stromman, 2011), and thus provide a good basis for comparisons. Climate change addresses the effects of increasing temperature in the lower atmosphere. The main contributors to climate change are carbon dioxide (CO_2), methane (CH_4) and nitrous oxides (N_2O). CCP is expressed as CO_2 equivalents (CO_2-eq.), i.e. the effects are expressed relative to the effects of CO_2. Terrestrial acidification results from the release of protons into terrestrial or aquatic ecosystems. The primary contributors are sulfur oxides (SO_x), nitrogen oxides (NO_x) and ammonia (NH_3). Acidification potential is expressed as SO_2 equivalents (SO_2-eq.), i.e. the potential is expressed in terms of the potential of SO_2. Eutrophication is caused by nutrient enrichment, which leads to increased aquatic plant production and oxygen depletion (when these plants decompose in the bottom layer) in aquatic ecosystems. Substances containing nitrogen (N) or phosphorus (P) are potential contributors to nutrient enrichment. Marine eutrophication potential is expressed as kg N-eq. and fresh water eutrophication is expressed as kg P-eq. Photochemical oxidant formation is the result of reactions between NO_x and volatile organic compounds (VOC) exposed to UV radiation. The principal precursors of tropospheric ozone are NOx, VOC's (including CH_4) and CO. Photochemical oxidant formation is expressed as kg NMVOC (non-methane volatile organic carbon compound) (Stranddorf et al., 2005). Fossil fuel depletion refers to the decreasing availability of fossil fuels as a result of their exploitation, and is expressed as kg oil-eq. The SimaPro 8.0.3 software (PRé Consultants, 2017) was used for the computational implementation of the life cycle inventory data and to determine the environmental profiles of the two studied scenarios.

2.6. Sensitivity analysis

A sensitivity analysis was conducted to overcome uncertainties and investigate how various factors influence the environmental impacts of the studied systems. These factors included:

- Longer transportation distances from landing to terminal. The container trucks and trailers used to transport pellets (landing-based scenario) and wood chips (terminal-based scenario) covered a new distance of 200 km – one way and empty return.
- Variation of biomass concentration at landing. A 50% increase and decrease in biomass concentration at the landing per harvesting site was tested. Only the transportation stage was affected by this variation since the productivity of the chipper, fractioning machine, drying system and pelletizer did not change with variation in biomass concentration. Therefore, the environmental impacts per functional unit produced by chipping, fractioning, drying and pelleting were independent of the amount of biomass processed (when the dryer containers work at maximum capacity).
- Increase in pelletizer capacity to 300 kg/h. The increase in pelletizer capacity affected the pelletizing process (more powerful pelletizer: 22 kW instead of 15 kW), the drying process (two more dryer containers were necessary and a more powerful hot air generator and fan: 12.2 kW instead of 5.8 kW), screw conveyors and hammer mill (time consumption was the same as for the pelletizer), and transportation of workers (the number of trips from terminal or landing to accommodation were reduced by half).
- Electricity at the terminal. The effects of using electricity from the power grid at the forest terminal instead of a diesel generator were tested. Electricity, low voltage {SE}| market for | Alloc Def, U from ecoinvent database® was used in the sensitivity analysis.
- Electric heater for drying sieved chips. Since the fine fraction obtained after fractioning represents a low quality fuel that could cause ash-melting, feeding problems, and inefficient combustion, the alternative of using an electric heater was analyzed.

- Decreased productivity in the landing-based scenario. The terminals can be expected to have more available space for structuring pellet production in a more efficient way than at the landing. Therefore, a 10% productivity reduction was applied to pelleting and drying at the landing, along with a 30% reduction in loader productivity (Lindroos et al., 2011).

3. Results and discussion

The quantification and comparison of the environmental profiles of different production stages of the landing- and terminal-based scenarios, and the identification of the main factors that influence the production of pellets are key findings in the present study. The landing- and terminal-based scenarios showed similar environmental profiles (Table 3). The ratio between the energy spent to produce pellets and their energy content was 0.23 for both scenarios.

3.1. Hotspots in the production systems

When all of the production stages were considered, pelleting was the stage that exhibited the highest emissions, followed by transportation, drying, chipping and fractioning (Table 3). Within the pelleting stage, pelletizing and hammer-milling showed the highest environmental impacts due to high time and energy consumption (Table 2). In terms of CCP, these processes emitted 93.2 kg and 32.6 kg CO_2-eq., respectively, which represent 54% and 19% of the GHG emissions arising from this stage. The diesel fuel burned in the generator to produce electricity represented 99% of the GHG emissions in both processes. The pelletizing process was also the most relevant process within the pelleting stage in terms of TAP, MEP, POFP and FDP, as it generated between 54% and 56% of the total emissions depending on which environmental impact was considered. Within the drying stage, the drying process generated most of the emissions due to high time and energy consumption of the hot air generator (Table 2). However, the use of fines (by-product from the fractioning process) as energy source in the bio-boiler avoided the use of external fuel in the drying process, which represents an important advantage of the system. Within the transportation stage, transportation of workers from landing or terminal to accommodation accounted for the largest environmental impact. This is due to the high time consumption of the pelletizer (7.3 h/ODt) and because the system operates continuously 24 h per day. This continuous operation requires tree shifts per day, and this means six trips per day to transport workers. In terms of CCP, this process emitted 28.8 kg CO_2-eq. in both the landing- and terminal-based scenarios. This represents around 75% of the total GHG arising from the transportation stage. When TAP, FEP, MEP, POFP and FDP are analyzed, this percentage varies from 55% to 85% depending on which environmental impact and scenario considered. The use of electrified cars or biodiesel from sustainable sources instead of diesel fuel would reduce these impacts. We considered the same travelling distances for workers in both scenarios even though it in practice would be probable that terminal workers have shorter travelling distances than landing workers, especially if the terminal is located close to a small village. If this is the case, the transportation stage in the terminal-based scenario would generate lower emissions. The other process within this stage with a significant environmental impact contribution was the transportation of pellets (landing-based scenario) or wood chips (terminal-based scenario). In terms of CCP, this process emitted 6.8 kg CO_2-eq. in the landing-based scenario and 8.6 kg CO_2-eq. in the terminal-based scenario.

3.2. Differences between scenarios

Pelleting and drying had the same environmental impacts in both scenarios since all of the variables in these stages were the same. The transportation stage, although similar in both scenarios, had important differences between processes within. The landing-based scenario required more trucks to relocate the equipment; however, the environmental impacts of the transportation stage in this scenario were lower because the transportation of pellets instead of chips was more efficient. Although the fractioning stage was similar in both scenarios (Table 3), there were important differences in how the machinery operated. In the landing-based scenario, the chipper, fractioning machine and wind-sifter worked as one unit. Therefore, the slowest machine determined the productivity of the unit; in this case, the chipper slowed down the fractioning machine. In contrast, the chipper and fractioning machine worked independently in the terminal-based scenario since the chipping process took place at the forest site while sieving occurred at the terminal. Therefore, the productivity of the fractioning machine in the terminal-based scenario was only limited by wind-sifter productivity. However, the piling and loading of wood chips onto the fractioning machine was necessary in the terminal-based scenario. For this reason, there was almost no difference in emissions between the scenarios at this stage. The biggest difference between scenarios came from the chipping stage (Table 3). The CCP, TAP, MEP, POFP and FDP values for this stage were approximately 12% higher in the terminal-based scenario. This difference was due to the piling of wood chips upon arrival at the terminal that occurs in the terminal-based scenario. This operation was not necessary in the landing-based scenario since the wood chips were loaded directly from the chipper to the fractioning machine.

3.3. Sensitivity analysis results

The results of increasing the transportation distance to 200 km in the terminal- and landing-based scenarios increased all the environmental impact categories (Table 4). This increase was

Table 3
Characterization results per functional unit (deliver of one ODt of pellet from forest to storage) corresponding to each production stage in landing-based and terminal-based scenarios. Acronyms: CCP, climate change potential; TAP, terrestrial acidification potential; FEP, fresh water eutrophication potential; MEP, marine eutrophication potential; POFP, photochemical oxidant formation potential; FDP, fossil fuel depletion potential.

Impact category	Landing-based scenario					Total	Terminal-based scenario					Total
	Chipping	Fractioning	Drying	Pelleting	Transportation		Chipping	Fractioning	Drying	Pelleting	Transportation	
CCP (kg CO_2-eq.)	16.2	11.1	37.4	172	38.2	275	18.5	10.9	37.4	172	38.7	278
TAP (kg SO_2-eq.)	0.12	0.08	0.45	1.6	0.12	2.4	0.14	0.08	0.45	1.6	0.12	2.4
FEP (g P-eq.)	0.89	1.8	2.4	7.8	6.3	19.2	1.4	2.4	2.4	7.8	6.2	20.2
MEP (g N-eq.)	7.2	4.6	28.6	103	5.3	149	8.2	4.2	28.6	103	5.3	149
POFP (kg NMVOC)	0.21	0.13	0.79	3.0	0.15	4.2	0.24	0.12	0.79	3.0	0.15	4.3
FDP (kg oil-eq.)	5.4	3.5	11.7	56.1	12.7	89.4	6.1	3.4	11.7	56.1	12.8	90.1

mostly influenced by the wood chip transportation process in the terminal-based scenario, where the GHG emissions increased from 8.6 kg CO_2-eq. (38 km transportation distance) to 45.7 kg CO_2-eq. (200 km transportation distance). For the landing-based scenario, this increase was largely influenced by the pellet transportation process, which increased GHG emissions from 6.8 kg CO_2-eq. to 36.0 kg CO_2 eq. The GHG emission difference between the transportation stages of the scenarios increased from 1.4% to 11.1%.This noticeable difference stems from better truck payloads in the landing-based scenario, which were a result of pellets being denser and having a lower moisture content than wood chips. This difference will become more apparent as transportation distances increase and if higher truck payloads are used.

An increase in pelletizer capacity by 100%–300 kg/h decreased the emissions by between 22% and 25% (depending on the environmental impact considered) in both landing- and terminal-based scenarios (Table 5). Although a higher capacity requires more powerful machinery, the production time decreases. Therefore, the environmental impacts per functional unit are also reduced (Table 5). However, an increase in pelletizer capacity would require more land for the equipment, and this could be problematic for the landing-based scenario.

The results showed that an electrified terminal (with a bio-boiler) reduced CCP, TAP, MEP, POFP and FDP by 68%, 78%, 80%, 83% and 71%, respectively (Fig. 3). However, FE increased by 26%. In terms of CCP, the drying and pelleting stages were the most affected, and showed a 93% and 90% reduction in emissions, respectively, when compared to using diesel fuel as the energy source. The shift from using diesel fuel as the energy source to an electrified terminal reduced the ratio between energy spent to produce pellets and their energy content from 0.23 to 0.15. However, this reduction will vary depending on the electricity mix of the region considered. The Swedish renewable energy share amounted to 52% in 2013 (Swedish Energy Agency, 2015). Therefore, the expected environmental impacts of production processes using Swedish electricity would be lower than the same processes using electricity with a lower percentage of renewables.

Other factors had a lower influence on the system environmental performance:

Increasing and decreasing 50% in biomass concentration at the landing had a limited effect on the results since only the transportation stage was affected. The increase in emissions due to a reduction of biomass concentration varied from 2% in terminal-based scenario to 4% in the landing-based scenarios; the emission reduction due to an increase in biomass concentration was around 1%. The effect on the landing-based scenario was slightly higher than on the terminal-based scenario since the relocation of chipper, fractioning machine, loader, drying and pelletizing units, and storage containers were affected by the amount of biomass at landing (the environmental impacts of the mentioned processes were divided by the total amount of ODt of pellets produced at the harvesting site). On contrast, only the relocation of chipper and chipper worker was affected by the biomass concentration at the landing in the terminal-based scenario.

Using an electric heater instead of a bio-boiler to dry the wood chips increased the GHG emissions with 8.3 kg CO_2-eq. and 37.2 kg CO_2-eq. when compared to using a bio-boiler in a non-electrified and electrified terminal, respectively. TAP, FEP, MEP and FDP increased by 0.08 kg SO_2-eq., 0.02 kg P-eq., 0.006 kg N-eq., and 9 kg oil-eq., respectively, when an electric heater was used instead of a bio-boiler in an electrified terminal. In contrast, POFP decreased by 0.02 kg NMVOC when an electric heater was used.

Finally, a 10% decrease in the productivity of machinery in the landing-based scenario increased all of the environmental impacts by approximately 8%, except for FEP, which showed a 5% increase (Table 6).

3.4. Comparison with related studies

Conventional pellet production chains from sawdust, cutterdust and roundwood were previously analyzed by Hagber et al. (2009). The authors applied a cradle-to-gate approach to centralized systems in Sweden. Their results showed emissions ranging from 56 to 74 kg CO_2-eq. per ODt of pellets for all three types of raw materials. These values are in agreement with Sikkema et al. (2010), who reported that the production of pellets in a pellet plant in Sweden using sawdust as a feedstock results in GHG emissions of around 50 kg CO_2-eq. per t of pellets. These results are much lower than those reported in other published pellet production studies. For example, Laschi et al. (2016) showed that the production of 1 t of packed pellets results in 400 kg CO_2-eq. in Italy. The production of the electricity required by the system was identified as the most important factor in pellet production, as it caused 93% of the emissions. In fact, Hagber et al. (2009) showed that if electricity from coal instead of the Swedish electricity mix had been used in their study, then the GHG emissions would have been between five and six times greater. The GHG emissions in this study were around 270 kg CO_2-eq. per ODt of pellets. However, when the Swedish electricity mix was used instead of diesel fuel, the GHG emissions reduced to 87 kg CO_2-eq. per ODt. With the aim of comparing the results of the gate-to-gate approach of the present study (logging residues were already at landing) with the ones corresponding to the cradle-to-gate approach from Hagber et al. (2009), the extraction of logging residues from the forest to the road side would need to be added. The GHG emissions of this process would add approximately 16 kg CO_2-eq. per ODt, according to the value reported by De La Fuente et al. (2017) and the specific biomass losses of this study.

3.5. Limitations of the study

The loading, un-loading and set-up times of machinery were not included in the analysis. If they had been included, the environmental impact of the landing-based scenario would have been

Table 4
Sensitivity analysis of increasing transportation distances to 200 km (one way). Characterization results of the transport stage in the landing- and terminal-based scenarios. Acronyms: CCP, climate change potential; TAP, terrestrial acidification potential; FEP, fresh water eutrophication potential; MEP, marine eutrophication potential; POFP, photochemical oxidant formation potential; FDP, fossil fuel depletion potential.

Impact category	Landing (transportation of pellets)	Terminal (transportation of wood chips)
CCP (kg CO_2-eq.)	67.4	75.8
TAP (kg SO_2-eq.)	0.24	0.28
FEP (g P-eq.)	9.6	9.6
MEP (g N-eq.)	12.1	13.9
POFP (kg NMVOC)	0.35	0.40
FDP (kg oil-eq.)	23.6	26.4

Table 5
Sensitivity analysis of increasing pelletizer capacity to 300 kg/h. Characterization results of the drying, pelleting and transportation stages in landing- and terminal-based scenarios. Acronyms: CCP, climate change potential; FDP, fossil fuel depletion potential; FEP, fresh water eutrophication potential; MEP, marine eutrophication potential; POFP, photochemical oxidant formation potential; TAP, terrestrial acidification potential.

Impact category	Landing-based scenario			Terminal-based scenario		
	Drying	Pelleting	Transportation	Drying	Pelleting	Transportation
CCP (kg CO_2-eq.)	37.9	118	24.1	37.9	118	24.3
TAP (kg SO_2-eq.)	0.46	1.09	0.08	0.46	1.09	0.08
FEP (g P-eq.)	1.7	6.8	3.6	1.7	6.8	3.6
MEP (g N-eq.)	29.4	69.7	3.8	29.4	69.7	3.8
POFP (kg NMVOC)	0.81	1.99	0.11	0.81	1.99	0.11
FDP (kg oil-eq.)	12.0	38.3	8.2	12.0	38.3	8.2

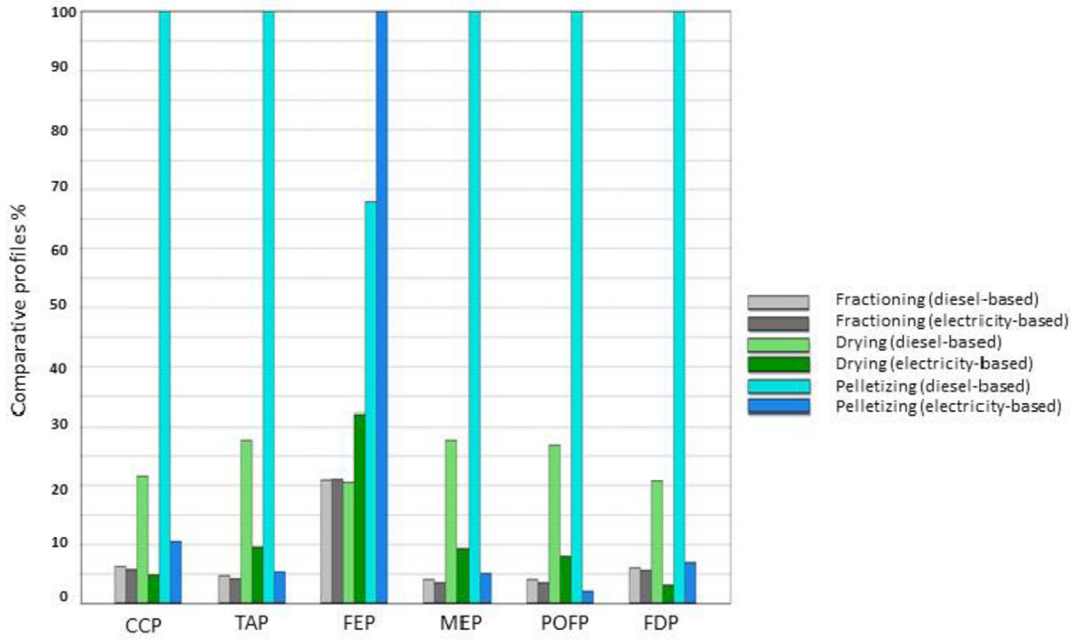

Fig. 3. Comparative profiles of the fractioning, drying and pelleting production stages in the terminal-based scenario when being powered by either diesel fuel (diesel-based) or electricity (electricity-based).

Table 6
Sensitivity analysis of a 10% productivity decrease in pelletizing and drying, as well as a 30% productivity decrease in loading, within the landing-based scenario. Characterization results of production stages in landing-based scenario. Acronyms: CCP, climate change potential; TAP, terrestrial acidification potential; FEP, fresh water eutrophication potential; MEP, marine eutrophication potential; POFP, photochemical oxidant formation potential; FDP, fossil fuel depletion potential.

Impact category	Landing-based scenario				
	Chipping	Fractioning	Drying	Pelleting	Transportation
CCP (kg CO_2-eq.)	16.2	11.5	41.1	188	39.3
TAP (kg SO_2-eq.)	0.12	0.83	0.48	1.18	0.12
FEP (g P-eq.)	0.89	1.8	2.6	8.4	6.5
MEP (g N-eq.)	7.2	4.8	30.8	112.5	5.4
POFP (kg NMVOC)	0.21	0.14	0.85	3.2	0.15
FDP (kg oil-eq.)	5.4	3.7	12.9	61.2	13.0

greater due to the relocation of machinery from one harvesting site to the next. To overcome this uncertainty, a productivity decrease for the landing-based scenario was included in the sensitivity analysis. The results showed a relevant increase in the environmental impacts when productivity decreased (Table 6). Furthermore, we assumed that the bio-boiler utilized to generate heat and dry the wood chips only ran on fuel from the fine fractions (by-product) from the fractioning process. A mixture that includes wood chips may be necessary to improve the combustion in the bio-boiler. In this case, the amount of pellets produced would be reduced and the environmental impacts per functional unit from the relocation of equipment would increase. Another assumption was the linear relation in the drying process between time and moisture content. Both of these assumptions should be tested in the field to determine their validity. Finally, the fine fractions that were not burned in the bio-boiler were piled in both scenarios. In the terminal-based scenario, this by-product could be further used as fuel or other products. In the landing-based scenario, the fine fraction could be transported to the terminal or spread in the forest. This last option would be desirable if biomass was extracted from forests with relatively poor soils because fines have high nutrient content. This process would have a small effect in the environmental impacts of the landing-based scenario since only around 0.2 l of diesel/ODt of pellets produced would be needed if a tractor time consumption of 0.1 h/ODt (Hakkila, 1989) is assumed.

A limitation of the present study is that the operational and system management costs were not considered in the analyses. The operational costs of forest operations are generally strongly correlated with the operational consumption of diesel fuel, and therefore also strongly correlated with the productivity and degree of

technical utilization. On the other hand, the system management cost is strongly correlated with the size and complexity of the system. Thus, additional analysis that considers the operational and management costs of the systems are necessary before either one of the systems is recommended.

4. Conclusions

This study employed a life cycle assessment approach to modeling landing- and terminal-based mobile production scenarios for pelletizing logging residues in Northern Sweden. The results showed that both scenarios had similar environmental profiles. The pelleting, transportation and drying stages were identified as *hotspots* in the production systems. These production stages accounted for 62%, 14% and 14% of the total GHG emissions, respectively. On contrast, the fractioning stage only represented around 4% of the total GHG. However, this production stage provided important benefits for the whole system: fractioning improved the pellet quality by reducing the fine fractions and, at the same time, the use of fines as energy source in the bio-boiler avoided the use of external fuel in the drying process.

The key factors influencing the system were the use of electricity at terminal, the increase of pelletizer capacity, and longer transportation distances. The use of a Swedish electricity mix in the terminal-based scenario reduced all of the environmental impacts by between 68% and 83%, with the exception of FE, which increased by 26%. A 200% increase in pelletizer capacity reduced emissions by 22%–25% depending on the environmental impact considered. Finally, longer transportation distances favored the landing-based scenario since pellet transportation was more efficient than wood chip transportation. However, the emission reduction in the transportation stage in the landing-based scenario was much lower than the emissions reduction achieved when the Swedish electricity mix was used in the terminal-based scenario. Therefore, an electrified mobile pellet production system with high operation efficiency situated at a terminal close to the harvesting sites would be, from an LCA point of view, a better option for pelletizing Nordic logging residues than a mobile pellet plant operating directly at the harvesting sites. Important aspects to consider in further research are related to the inclusion of operational and system management costs that should be performed before either one of the presented systems are chosen for a real-life setting.

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